Nitrogen Application Levels Based on Critical Nitrogen Absorption Regulate Processing Tomato Productivity, Nitrogen Uptake, Nitrate Distribution, and Root Growth in Xinjiang, China: Postprint

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Abstract

The unreasonable nitrogen (N) supply and low productivity are the main factors restricting the sustainable development of processing tomatoes. In addition, the mechanism by which the N application strategy affects root growth and nitrate distributions in processing tomatoes remains unclear. In this study, we applied four N application levels to a field (including 0 (N0), 200 (N200), 300 (N300), and 400 (N400) kg/hm2) based on the critical N absorption ratio at each growth stage (planting stage to flowering stage: 22%; fruit setting stage: 24%; red ripening stage: 45%; and maturity stage: 9%). The results indicated that N300 treatment significantly improved the aboveground dry matter (DM), yield, N uptake, and nitrogen use efficiency (NUE), while N400 treatment increased nitrate nitrogen (NO3—N) residue in the 20–60 cm soil layer. Temporal variations of total root dry weight (TRDW) and total root length (TRL) showed a single-peak curve. Overall, N300 treatment improved the secondary root parameter of TRDW, while N400 treatment improved the secondary root parameter of TRL. The grey correlation coefficients indicated that root dry weight density (RDWD) in the surface soil (0–20 cm) had the strongest relationship with yield, whereas root length density (RLD) in the middle soil (20–40 cm) had a strong relationship with yield. The path model indicated that N uptake is a crucial factor affecting aboveground DM, TRDW, and yield. The above results indicate that N application levels based on critical N absorption improve the production of processing tomatoes by regulating N uptake and root distribution. Furthermore, the results of this study provide a theoretical basis for precise N management.

Full Text

Preamble

Nitrogen Application Levels Based on Critical Nitrogen Absorption Regulate Processing Tomato Productivity, Nitrogen Uptake, Nitrate Distributions, and Root Growth in Xinjiang, China

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Abstract: Unreasonable nitrogen (N) supply and low productivity are the main factors restricting the sustainable development of processing tomatoes. Additionally, the mechanism by which N application strategy affects root growth and nitrate distribution in processing tomatoes remains unclear. In this study, we applied four N application levels to a field (0 (N0), 200 (N200), 300 (N300), and 400 (N400) kg/hm^2) based on the critical N absorption ratio at each growth stage (planting to flowering: 22%; fruit setting: 24%; red ripening: 45%; and maturity: 9%). The results indicated that the N300 treatment significantly improved aboveground dry matter (DM), yield, N uptake, and nitrogen use efficiency (NUE), while the N400 treatment increased nitrate nitrogen (NO_3^--N) residue in the 20–60 cm soil layer. Temporal variations in total root dry weight (TRDW) and total root length (TRL) followed a single-peak curve. Overall, the N300 treatment improved the secondary root parameter of TRDW, whereas the N400 treatment improved the secondary root parameter of TRL. Grey correlation coefficients indicated that root dry weight density (RDWD) in the surface soil (0–20 cm) had the strongest relationship with yield, while root length density (RLD) in the middle soil layer (20–40 cm) also showed a strong relationship with yield. Path analysis revealed that N uptake is a crucial factor affecting aboveground DM, TRDW, and yield. These results demonstrate that N application levels based on critical N absorption improve processing tomato production by regulating N uptake and root distribution, providing a theoretical basis for precise N management.

Keywords: critical N absorption; nitrogen use efficiency (NUE); beta model; total root dry weight (TRDW); root growth; processing tomato

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Introduction

Globally, nitrogen (N) fertilizer use has contributed to alleviating food security challenges, particularly in achieving high crop yields (Wang et al., 2018; Matiwane et al., 2019). China is among the countries with the largest N application rates worldwide, where unreasonable N fertilizer application is prevalent (Li and Lin, 2021). However, increasing N fertilizer input does not sustainably increase yield due to declining nitrogen use efficiency (NUE) (Liu et al., 2019; Liang et al., 2020). Moreover, excessive N application leads to soil acidification and groundwater pollution in farmlands (Xiang et al., 2007; Gu et al., 2019). Therefore, adopting scientific N fertilizer application practices to improve NUE and reduce environmental pollution has become imperative for sustainable agricultural development (Li and Lin, 2021).

Critical N absorption is an important parameter for evaluating NUE during specific growth periods (Ulrich, 1952). In studies conducted on pastures without N limitation, the relationship between critical N concentration and aboveground dry matter (DM) has been established. The critical N concentration was defined through continuous verification and parameter modification and has been applied to most C3 and C4 plants (Greenwood et al., 1990; Wang et al., 2013). Through N nutrition diagnosis, field application rates of 240–320 kg/hm^2 N have been shown to satisfy rice plant growth (Ata-Ul-Karim et al., 2014). Although the critical N concentration model provides total N application rates, the critical N application rates at each growth stage have not been widely implemented in agricultural practice. Therefore, the key to accurate N application lies in determining N application rates at each growth stage based on the critical N concentration model.

Processing tomato is among the vegetable crops with the largest global cultivation area (Farneselli et al., 2015) and contains important nutrients required by the human body (Lu et al., 2019). China has become a major producer and supplier of processing tomatoes, second only to the United States (Elia and Conversa, 2012). In recent years, drip irrigation technology has developed rapidly in China, significantly impacting the root architecture of processing tomatoes compared with traditional flood irrigation (Wang et al., 2022). Combined with the advantages of drip irrigation under mulch, understanding the coupling mechanism of N absorption and plant growth in processing tomatoes is vital for dryland agriculture development (Zotarelli et al., 2009; Li et al., 2016; Kang et al., 2017).

The spatial distribution of plant roots plays a crucial role in soil–shoot–atmosphere interactions (Liu et al., 2018). Soil nutrients and moisture become heterogeneous due to root interactions, which impacts community structure and composition (Day et al., 2003). Conversely, root spatial distribution responds differently to soil nutrient and moisture conditions (Sun et al., 2018). For example, studies have shown that soil moisture altered root architecture and biomass of soybean (Fenta et al., 2014), while N deficiency resulted in notable changes in lateral roots of cotton (Zhu et al., 2022). In this study, we hypothesize that N application strategy improves processing tomato productivity by regulating root growth and nitrate distribution. Under mulched drip irrigation, critical N absorption of processing tomatoes was used to calculate critical N demand at each growth stage (Tei et al., 2002). Therefore, this research aimed to: (1) investigate the effects of N application levels on processing tomato productivity, N absorption, and nitrate nitrogen (NO_3^--N) residue; (2) explore the dynamic root distribution of processing tomatoes under different N application levels; and (3) clarify the regulatory mechanism of N application based on the critical N absorption model on productivity and root distribution of processing tomatoes.

2.1 Experiment Site

The field experiment was conducted from April 2018 to July 2019 at the agricultural experimental station of Shihezi University (44°21 N, 86°04 E; 450 m) in Shihezi City, Xinjiang Uygur Autonomous Region, China. Precipitation during the processing tomato growing season was 76 mm in 2018 and 114 mm in 2019, mainly concentrated in May. The average daily temperatures during the growing season were 24.5°C in 2018 and 23.1°C in 2019 (Fig. 1 [Figure 1: see original paper]). The chemical properties of topsoil (0–40 cm) are shown in Table 1 .

Fig. 1 Daily precipitation, maximum temperature (Tmax), and minimum temperature (Tmin) during the growing season of processing tomatoes in 2018 (a) and 2019 (b)

Table 1 Initial chemical properties of topsoil (0–40 cm) in 2018 and 2019

Total N (g/kg)	Available P (g/kg)	Available K (g/kg)	Organic matter
Note: N, nitrogen; P, phosphorus; K, potassium.			

2.2 Experimental Design and Field Management

Wang et al. (2013) developed a statistical method for constructing the critical N concentration dilution curve of processing tomatoes based on DM in northern Xinjiang. The critical N concentration dilution curve was calculated as follows:

$$N_c = 4.352DM^{-0.43}$$

where N_c is the N concentration (%). Critical N uptake was calculated by the following formula:

$$N_{upt} = 43.521 DM^{0.57}$$

where N_{upt} is the N uptake (kg/hm^2). The proportion of the N application rate at each growth stage to the total N application rate was determined using N uptake (Jing et al., 2020). We calculated the increase in N uptake at each growth stage according to the increase in DM of processing tomatoes at that specific stage, representing an increase in the critical N application rate. Therefore, the proportion of the N application rate at each growth stage to the total N application rate during the entire growth period was determined as follows: planting stage to flowering stage: 22%; fruit setting stage: 24%; red ripening stage: 45%; and maturity stage: 9%.

The experiment followed a completely randomized block design with three replicates. We established four N application levels: 0, 200, 300, and 400 kg/hm^2 (designated as N0, N200, N300, and N400, respectively). N fertilizer was applied as top dressing based on the proportion for each growth stage. Additionally, 210 kg/hm^2 of phosphate fertilizer and 150 kg/hm^2 of potassium fertilizer were simultaneously applied as base fertilizers.

Before the experiment, healthy seeds of processing tomatoes (Rieger 87-5) were sown in pots and provided with sufficient water. Seedlings were transplanted to the field on 29 April 2018 and 26 April 2019 when four true leaves appeared. The drip line arrangement was set as "one mulch, two drip lines, and two rows of processing tomatoes," with a plant spacing of 30 cm and row spacing of 60 cm (Fig. 2 [Figure 2: see original paper]). Each experimental plot area was 86.4 m^2 (7.2 m × 12.0 m). Irrigation was performed every 7 to 10 days, with each irrigation amount controlled using a water meter. Irrigation was postponed in the event of rainfall. The total irrigation volume during the entire growth period was approximately 4700 m^3/hm^2.

Fig. 2 (a) Overhead view of the planting pattern of processing tomatoes in the experimental field; (b) Stereoscopic view of root samples taken using the layered-mining method

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2.3.1 Measurement of Aboveground Dry Matter (DM), Nitrogen (N) Uptake, Yield, and Nitrogen Use Efficiency (NUE)

At harvest in 2018 and 2019, three representative plants were randomly collected from each plot to determine aboveground DM and N uptake. The aboveground parts were oven-dried at 75°C to constant weight, and DM was determined gravimetrically. Subsequently, oven-dried plant samples were pulverized and screened through a 0.1 mm sieve. An appropriate amount of fine powder was digested with H_2SO_4-H_2O_2 to determine N concentration using the Kjeldahl method. N uptake was calculated as the product of DM and N concentration. Processing tomatoes were manually harvested from a 2.4 m^2 area per plot to determine yield. NUE (%) was calculated as follows:

$$\text{NUE} = \frac{C_N - C_0}{N_a} \times 100$$

where C_N is N uptake by plants in N-applied areas (kg/hm^2), C_0 is N uptake by plants in areas without N application (kg/hm^2), and N_a is the amount of N fertilizer applied (kg/hm^2).

2.3.2 Soil Nitrate Nitrogen (NO_3^--N) Content

After harvest, soil samples were collected from 0–80 cm layers at 20 cm intervals using an earth drill with a 2.5 cm diameter. Samples were dried at room temperature, then milled and screened. NO_3^--N content was determined using a 1 mol/L KCl solution through the ultraviolet spectrophotometer method.

2.3.3 Root Sampling and Analysis

In each plot, processing tomato roots were regularly harvested using the excavation method. Because roots were mainly distributed in the 0–60 cm soil layer, and 30 cm around the plant was the concentration area of water and nutrients under drip irrigation (Jing et al., 2021), roots were collected in a soil column (30 cm × 30 cm × 60 cm) at 20 cm intervals (Fig. 2b). Root samples were obtained using the manual flushing method and scanned with a specialized root scanner (Epson Perfection V700 Photo, EPSON, Nagano, Japan). Root length was determined by analyzing scanned images using the Winrhizo Pro Vision 5.0 analysis program. Finally, root samples were dried at 75°C for 12 h to obtain root dry weight.

Root dry weight and root length per soil layer in the unit area were expressed by the following formulas:

$$\text{RDW} = \frac{D}{S}$$

$$\text{RL} = \frac{L}{S}$$

where RDW is root dry weight (g/m^2), D is root dry weight per soil layer (g), S is soil area (m^2), RL is root length (m/m^2), and L is root length per soil layer (m). Total root dry weight (TRDW; g/m^2) or total root length (TRL; m/m^2) was the sum of root dry weight or root length across all soil layers.

Similarly, root dry weight density and root length density in unit soil volume were expressed by the following formulas:

$$\mathrm{RDWD} = \frac{D}{V}$$

$$\mathrm{RLD} = \frac{L}{V}$$

where RDWD is root dry weight density (g/m^3), RLD is root length density (m/m^3), and V is soil volume (m^3).

2.3.4 Quantitative Analysis of Beta Model

The beta function of root growth rate can determine the relationship between growth rate and duration (Yin et al., 2002; Wang et al., 2014). The formula is as follows:

$$w = w_{max} \times \left(1 + \frac{t_e - t}{t_e - t_m}\right) \times \left(\frac{t}{t_e}\right)^{\frac{t_e}{t_e - t_m}}$$

where w is the growth parameter of root (TRDW or TRL), t is the number of days after planting (d), w_{max} is the maximum growth parameter of root when it grows to t_e day (g/m^2 or m/m^2 for TRDW or TRL, respectively), and t_m is the number of days when the root growth rate reaches the maximum value (d).

The average rate of root growth (c_a; (g/m^2) · d^{-1} or (m/m^2) · d^{-1} for TRDW or TRL, respectively) was expressed by the following formula:

$$c_a = \frac{w_{max}}{t_e}$$

The maximum root growth rate (c_m; (g/m^2) · d^{-1} or (m/m^2) · d^{-1} for TRDW or TRL, respectively) was expressed by the following formula (Yin et al., 2002):

$$c_m = \frac{w_{max}}{t_e} \times \left(\frac{t_e}{t_m}\right)^{\frac{t_e}{t_e - t_m}}$$

2.3.5 Grey Correlation Analysis

Grey correlation was evaluated using the method of Jia et al. (2020):

Step 1: Original data transformation by equalization:

$$x'_{ij} = \frac{x_{ij}}{\bar{x}_j}$$

where x'_{ij} is the equalized transformation value, x_{ij} is the actual value of index, and $\bar{x}_j$ is the average value of index j.

Step 2: Calculation of the correlation coefficient. The yield of processing tomatoes was used as the basic sequence, and root growth parameters in each soil layer were set as subsequences. The correlation coefficient was calculated by the following equation:

$$L_{0i}(K) = \frac{\Delta_{min} + \rho\Delta_{max}}{\Delta_{0i}(K) + \rho\Delta_{max}}$$

where $L_{0i}(K)$ is the correlation coefficient, Δ_{min} and Δ_{max} are the minimum and maximum values of absolute differences at any moment, respectively, ρ is the resolution ratio (set as 0.5), and $\Delta_{0i}(K)$ is the absolute difference between the two comparison sequences at moment K.

Step 3: Correlation calculation. We used the following equation:

$$r_{0i} = \frac{1}{N}\sum_{K=1}^{N} L_{0i}(K)$$

where r_{0i} is the correlation between subsequence i and the basic sequence, and N is the length of the comparison sequences.

Step 4: Testing the significance of the correlation coefficient. The t value was calculated using the following equation:

$$t = \frac{r_{0i}}{\sqrt{1 - r_{0i}^2}} \times \sqrt{n-2}$$

where $n - 2$ is the degree of freedom.

2.4 Statistical Analyses

Analysis of variance was conducted using SPSS 17.0 software. Path analysis was employed to assess relationships between indicators using SPSS 17.0 software. Least significant difference tests were used for significance analysis. Plotting was completed using Origin 9.0 software.

3.1 Aboveground DM, Yield, N Uptake, and NUE Under Different N Application Levels

N application levels significantly affected aboveground DM, yield, N uptake, and NUE of processing tomatoes ($P < 0.01$; Fig. 3 [Figure 3: see original paper]). Although results differed between the two years due to climatic factors, the same trends were observed across treatments in both years. The ranking of aboveground DM, yield, and N uptake across the four N application levels was N0 < N200 < N400 < N300. Furthermore, NUE was higher under N300 treatment compared to N200 and N400 treatments.

Fig. 3 Aboveground dry matter (DM; a), yield (b), nitrogen (N) uptake (c), and nitrogen use efficiency (NUE; d) under different N application levels in 2018 and 2019. N0, N200, N300, and N400 represent N application levels of 0, 200, 300, and 400 kg/hm^2, respectively. Different lowercase letters within the same year indicate significant differences among N application levels at $P < 0.05$. ** indicates significance at $P < 0.01$ level. Bars represent standard errors.

3.2 Dynamic Changes in Total Root Dry Weight (TRDW) and Total Root Length (TRL)

TRDW and TRL showed similar temporal variations in both years (Fig. 4 [Figure 4: see original paper]). Root growth parameters were fitted using the beta model, with determination coefficients (R^2) exceeding 0.85, indicating that the beta model effectively reflected root development. The root growth process under different N application levels showed a single-peak curve, characterized by slow growth, rapid growth, and then gradual decline. Differences in TRDW and TRL were observed under different N application levels (Table 2). During the two years, the ranking of maximum root growth parameters, average root growth rate, and maximum root growth rate was N0 < N200 < N400 < N300 for TRDW. Additionally, these values for TRL under N400 treatment were higher compared to other treatments.

Fig. 4 Beta model of variations in total root dry weight (TRDW; a and b) and total root length (TRL; c and d) under different N application levels in 2018 and 2019. The fitting curves represent the beta equation fitting curves for N application levels of 0, 200, 300, and 400 kg/hm^2.

Table 2 Secondary root parameters under different N application levels

Parameter	N Application Level	wmax (g/m^2 or m/m^2)^1	te (d)	tm (d)	ca ($(g/m^2) \cdot d^{-1}$ or $(m/m^2) \cdot d^{-1}$)^2	cm ($(g/m^2) \cdot d^{-1}$ or $(m/m^2) \cdot d^{-1}$)^2
TRDW	N0	134.34d	86.62a	53.80c	1.55d	2.59d
	N200	216.16c	84.99b	52.25c	2.54c	4.94a
	N300	403.28a	81.60c	60.47a	4.94a	8.12a
	N400	267.95b	79.90c	56.45b	3.35b	6.40b
TRL	N0	355.76c	69.16a	43.05b	5.14c	8.59c
	N200	408.77b	68.93a	41.14b	5.91b	9.61b
	N300	581.57a	71.61a	42.61b	8.12a	13.14a
	N400	596.53a	72.02a	47.24a	8.28a	14.48a

Note: N0, N200, N300, and N400 represent N application levels of 0, 200, 300, and 400 kg/hm^2, respectively. TRDW, total root dry weight; TRL, total root length; wmax, maximum root growth parameters; te, days when root growth parameter reaches maximum value; tm, days when root growth rate reaches maximum value; ca, average root growth rate; cm, maximum root growth rate. Different lowercase letters within the same year indicate significant differences among N application levels at $P < 0.05$. ^{1} wmax units are g/m^2 for TRDW and m/m^2 for TRL; ^{2} ca and cm units are $(g/m^2) \cdot d^{-1}$ for TRDW and $(m/m^2) \cdot d^{-1}$ for TRL.

3.3 Soil NO_3^--N Content, Root Dry Weight Density (RDWD), and Root Length Density (RLD) in Soil Profiles

At the harvest stage, soil NO_3^--N content showed an initial increase followed by a decrease with increasing soil depth under all treatments (Fig. 5 [Figure 5: see original paper]). The ranking of total soil NO_3^--N content across the four N application levels was N0 < N200 < N300 < N400. Remarkably, the N400 treatment resulted in significant accumulation of soil NO_3^--N in the 20–60 cm soil layer. Additionally, the vertical distribution of roots showed adaptive changes. Both RDWD and RLD decreased gradually with increasing soil depth (Fig. 6 [Figure 6: see original paper]). Roots were mainly distributed in the 0–20 cm soil layer. Within the 0–20 cm layer, the ranking of RDWD and RLD across the four N application levels was N0 < N200 < N400 < N300 and N0 < N200 < N300 < N400, respectively. In the 20–40 and 40–60 cm soil layers, RDWD and RLD under N300 treatment were higher compared to other treatments.

Fig. 5 Soil nitrate nitrogen (NO_3^--N) content in the 0–80 cm soil layers under different N application levels in 2018 (a) and 2019 (b). Bars represent standard errors.

Fig. 6 Changes in root dry weight density (RDWD; a and b) and root length density (RLD; c and d) in different soil layers under different N application levels in 2018 and 2019. Bars represent standard errors.

3.4 Grey Correlation Coefficients Between Yield and Root Density in Different Soil Layers

Under N application levels based on critical N absorption, the minimum grey correlation coefficient between yield and RDWD or RLD was observed in the 40–60 cm soil layer. The maximum grey correlation coefficient between yield and RDWD occurred in the 0–20 cm soil layer, while the maximum grey correlation coefficient between yield and RLD was observed in the 20–40 cm soil layer (Table 3). Additionally, N application levels affected the grey correlation coefficient in the 0–60 cm soil layer. For RDWD, the grey correlation coefficient of N300 treatment was higher than that of other treatments across different soil layers. For RLD, the grey correlation coefficient of N400 treatment was higher than that of other treatments in the 0–20 and 40–60 cm layers, while the grey correlation coefficient of N0 treatment was higher than that of other treatments in the 20–40 cm layer. These results indicated that RDWD in surface soil (0–20 cm) had the strongest relationship with yield, but its influence decreased with increasing soil depth. RLD in the 20–40 cm soil layer also had a strong relationship with yield, significantly impacting yield under N deficiency ($P < 0.05$).

Table 3 Grey correlation coefficients between root parameters in different soil layers with yield under different N application levels

Root Parameter	N Application Level	Soil Depth (cm)	Grey Correlation Coefficient
RDWD (g/m^3)	N0	0–20	0.859**
		20–40	0.757*
		40–60	0.727*
	N200	0–20	0.729**
		20–40	0.759*
		40–60	0.649*
	N300	0–20	0.651*
		20–40	-
		40–60	-
RLD (m/m^3)	N0	0–20	-
		20–40	0.651*
		40–60	-

Note: RDWD and RLD are root dry weight density and root length density, *respectively.* and ** indicate significant correlation coefficients at $P < 0.05$ and $P < 0.01$ levels, respectively.*

3.5 Path Analysis of Aboveground DM, TRDW, N Uptake, Soil NO_3^--N Content, and Yield

Path analysis was used to assess relationships among aboveground DM, TRDW, N uptake, soil NO_3^--N content, and yield (Fig. 7 [Figure 7: see original paper]). The direct impact degree on yield followed the order: N uptake > TRDW > aboveground DM > soil NO_3^--N content. Moreover, the coefficients of N uptake and TRDW on yield were significant ($P < 0.01$). N uptake significantly and positively affected TRDW and aboveground DM ($P < 0.05$). Additionally, aboveground DM and soil NO_3^--N content were negatively related to yield. These findings indicated that increased vegetative growth and soil N do not necessarily translate into continuous yield improvement and may result in plant overgrowth and N leaching.

Fig. 7 Path model among aboveground DM, TRDW, N uptake, soil NO_3^--N content, and yield. Blue lines represent positive relationships, while red lines represent negative relationships. The width of arrows represents the strength of significant standardized path coefficients. * and ** indicate significant path coefficients at $P < 0.05$ and $P < 0.01$ levels, respectively.

4.1 Productivity and N Uptake Responses to Various N Application Levels

Reasonable fertilization plans have proven effective in promoting aboveground DM and yield (Ronga et al., 2017; Banger et al., 2020). In this study, we implemented an N application strategy based on critical N absorption at each growth stage. Our results showed a positive correlation between N application rate and aboveground DM or yield of processing tomatoes within 300 kg N/hm^2. However, the 400 kg/hm^2 N application hindered aboveground DM and yield, consistent with findings by Farneselli et al. (2018). This could be explained by several mechanisms. First, adequate N input ensures root growth and water absorption, thereby promoting aboveground DM and yield. However, excessive N input causes inorganic N accumulation in soil, resulting in soil salinization (Cheng et al., 2021). Second, high N concentration directly reduces soil microbial activity by enhancing specific ion toxicity, thereby inhibiting root growth and nutrient absorption (Yan et al., 2021).

Reasonable regulation of soil N holds considerable potential for maintaining stable yield and NUE in arid areas (Zheng et al., 2021). In this study, the N300 treatment achieved the highest N uptake and NUE, while the N400 treatment resulted in the highest soil NO_3^--N content. Despite plastic film mulching increasing soil water storage, high N concentration accelerated soil moisture reduction due to excessive vegetative growth and increased transpiration rate (Long et al., 2021). Therefore, under water-deficit conditions, the migration rate of NO_3^--N to deep soil could be slower in the N400 treatment. Additionally, high N concentration inhibits plant N uptake and increases NO_3^--N residue (Yuan et al., 2018).

4.2 Root Growth Responses to Various N Application Levels

In this study, secondary root parameters were analyzed using the beta model. Overall, compared with N0 and N200 treatments, the N300 treatment improved the secondary root parameter of TRDW, while the N400 treatment improved the secondary root parameter of TRL. Wang et al. (2014) reported that crop community structures were optimized by maintaining high TRDW in the late growth period under reasonable planting modes. These improvements may be due to nutrient deficiency under N0 and N200 treatments, which decreased soil microbial activity and hindered root growth (Isobe et al., 2018). Additionally, nutrient deficiency in the late growth period blocked plant physiological metabolism (Zaman et al., 2021). Most processing tomato roots accumulated in the uppermost (0–20 cm) soil layer. Generally, plant root configuration is controlled by genetic factors (Clark et al., 2011; Ning et al., 2019). However, plant roots exhibit adaptive changes in response to specific environmental conditions in distinct growth environments (Martins et al., 2019).

Appropriate N concentration promoted root growth (Hackett, 1972; Drew, 1975; Postma et al., 2014), while high N concentration inhibited it (Forde and Lorenzo, 2001). This phenomenon was also observed across different soil layers in this study. Specifically, RDWD of the N300 treatment was highest compared to other treatments in the 0–20 cm soil layer, while RLD of the N400 treatment was largest. This could be attributed to two mechanisms. First, high N concentration inhibits biosynthesis and transport of indole acetic acid, thereby inhibiting taproot growth (Walch-liu et al., 2001). Second, lateral root growth is hindered by inhibition of dividing tissue activity (Zhang and Forde, 1998). Additionally, research has shown that high N concentration promotes regeneration of superficial capillary roots, which may explain the longer root length in topsoil of the N400 treatment. In this study, RLD of the N300 treatment was highest compared to other treatments in the 40–60 cm soil layer. Remarkably, increased RLD in deeper soil layers effectively facilitated nutrient and water absorption (Zhang et al., 2009; Jia et al., 2020).

4.3 Crucial Determinants of Productivity Promotion

Nitrogen is essential for normal plant metabolism and is the main limiting factor for crop yields (Shi et al., 2022). Distribution of carbohydrates among various plant organs ensures a balanced growth ratio between underground and aboveground parts, but applying N fertilizers can disrupt this growth balance (Lovelli et al., 2012). Thus, N fertilizers significantly affect biomass of plant shoots and roots (Sainju et al., 2017). Furthermore, N fertilization plays a crucial role in soil pore structure and microbial balance (Liang and Shi, 2021). Therefore, employing path analysis is necessary to understand relationships among N uptake, aboveground DM, TRDW, soil NO_3^--N content, and yield. The path model indicated that N uptake is a crucial factor affecting aboveground DM, TRDW, and yield. Moreover, aboveground DM and soil NO_3^--N content were negatively related to yield, suggesting increased vegetative growth and leaching risk. Notably, no significant negative correlation was observed between aboveground DM and yield, mainly due to vigorous nutritional growth of plants under N400 treatment. However, the N300 treatment obtained the highest yield. According to soil and plant nutrient status, plants use specialized vascular tissue to transport N, effectively regulating biomass distribution (Hermans et al., 2006; Litton et al., 2007; McCarthy and Enquist, 2007). However, due to soil water infiltration caused by rainfall and irrigation, N leaching was inevitable (Wang and Li, 2019). In conclusion, we confirmed the crucial role of N application based on critical N absorption in improving productivity, although the risk of NO_3^--N leaching still exists. Moreover, further validation is needed to understand the physiological mechanisms underlying processing tomato responses to critical N absorption.

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5 Conclusions

Under N application levels based on critical N absorption, the N300 treatment significantly improved processing tomato productivity and NUE, while the N400 treatment increased the risk of NO_3^--N leaching. Roots under N300 and N400 treatments showed increased growth, which promoted yield. While RDWD in surface soil (0–20 cm) had the strongest relationship with yield, RLD in middle soil (20–40 cm) also showed a strong relationship with yield. Additionally, N uptake was a crucial factor influencing aboveground DM, TRDW, and yield. Our results suggest that the 300 kg/hm^2 N application, based on the critical N absorption ratio (planting to flowering: 22%; fruit setting: 24%; red ripening: 45%; maturity: 9%), improved root distribution and soil NO_3^--N content while promoting processing tomato productivity.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Author Contributions

Conceptualization: DIAO Ming, SHI Wenjuan; Data curation: JING Bo; Methodology: DIAO Ming, SHI Wenjuan; Investigation: DIAO Ming; Formal analysis: JING Bo; Writing - original draft preparation: JING Bo; Writing - review and editing: DIAO Ming, SHI Wenjuan; Funding acquisition: DIAO Ming, SHI Wenjuan; Resources: DIAO Ming; Supervision: DIAO Ming; Project administration: DIAO Ming.

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Note: Figure translations are in progress. See original paper for figures.